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FROM AUTOMATION TO AUTONOMY
-TRENDS TOWARDS AUTONOMOUS COMBAT SYSTEMS-

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SUMMARY

The development, procurement and utilization of defense systems will in future be strongly influenced by affordability. A considerable potential for cost reduction is seen in the extended use of automation reaching as far as autonomous unmanned systems. Starting with conventional and intelligent automation issues, this paper will describe important enabling techniques and technologies as a prerequisite for the implementation of future autonomous systems with goal- and behavior-oriented features. Main emphasis is being placed on information technology with its computational and machine intelligence (CMI) techniques. The treatment of conceptional system approaches will be followed by design considerations and then a global methodology for the engineering of future autonomous systems will be dealt with.

Critical experiments for technology evaluation and validation will be mentioned together with a brief description of the main focus in future research.

1 INTRODUCTION

Tactical systems are implemented as Integrated Mission Systems (IMS) such as e.g. air and space defense systems. Key elements of IMS are - among others - platforms with sensors and effectors, ground based components with communication, command and control etc.

In technology, evolutionary progress is generally determined by the interaction between the "Requirements Pull (RP)" and the "Technology Push (TP)" (Fig. 1).

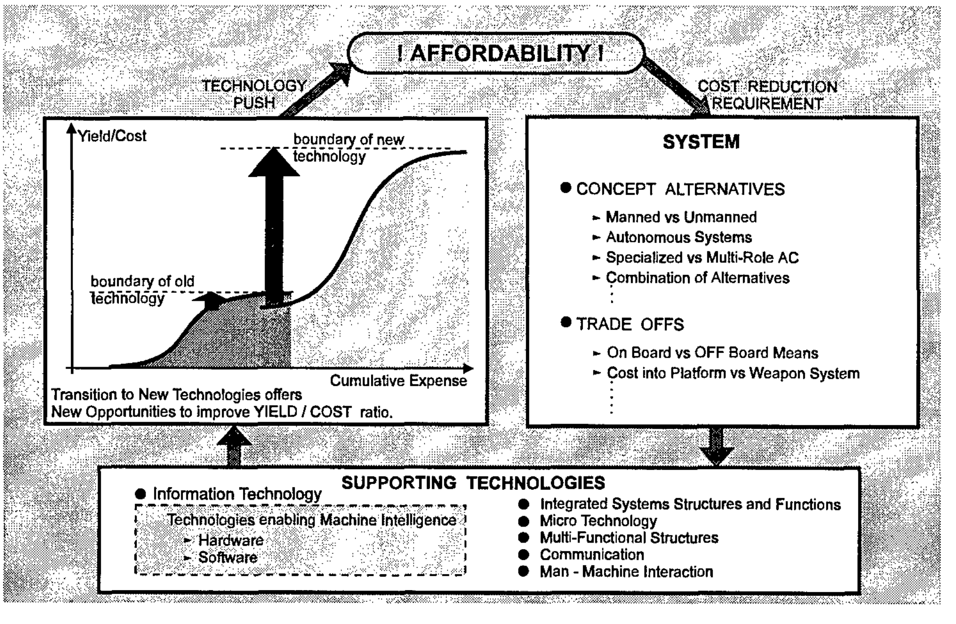


Figure 1: Requirements pull vs. technology push

Paper presented at the RTO SCI Symposium on "Advances in Vehicle Systems Concepts and Integration", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

Ever increasing requirements for more and more complex systems and their functions activate individual key technologies within the technological basis available or possibly to be created. However, new technologies - such as currently the new Information Technology (IT) - exert pressure towards increased requirements for new systems.

In the future progress primarily will be driven by economic aspects rather than by technological advances alone. Within this context "affordability" is of decisive importance. Advancing Technologies are essential for achieving unprecedented capabilities for new systems at affordable cost. Looking at Fig. 1 (upper left) the yield/cost ratio is plotted against the commulative expenses for old and new technologies (e.g. Information Technology). Considering the general performance potential, the transition to new technologies is mandatory to offer new opportunities and improved yield/cost ratios. Autonomous unmanned tactical systems surely are a viable step to cope with the cost reduction challenge and to improve cost effectiveness in the future.

2 INTELLIGENT AUTOMATION

Taking airvehicle as an example, the Unmanned (Uninhabited) Tactical Aircraft (UTA) or the Unmanned Combat Airvehicle (UCAV) are concepts to integrate advanced technologies into a complete tactical airpower system in order to enable a general purpose high performance aircraft to perform a full range of tethal missions without the physical presence of a pilot in the aircraft.

Figure 2 depicts the multi-dimensional closed loop guidance and control blockdiagram of an UTA resp. UCAV with the remote pilot or - more general - the operator being integrated through a bidirectional data link. Progressing from inside out the inner stabilization and control loop of the vehicle represents the lowest level of the hierarchical control structure. The next higher level performs flight path control followed by the mission and vehicle trajectory control as well as the weapon control functions beeing the highest level of the functional blockdiagram.

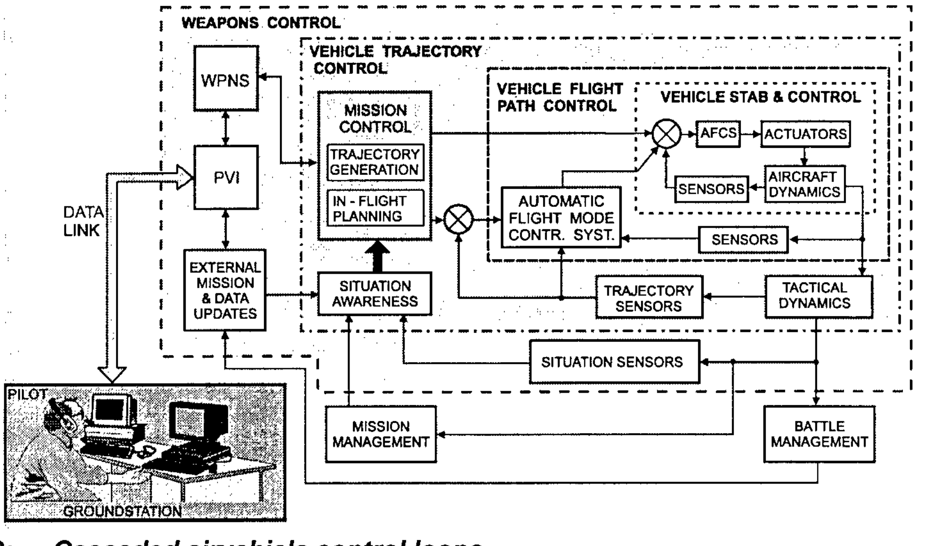


Figure 2: Cascaded airvehicle control loops

The key notions „automation" and „autonomy" are intimately connected with advances in Information Technology. Therefore emphasis is placed on this aspect.

Automation of most, if not all, of the said functions applying more or less conventional techniques such as algorithmic, numerical and expert system approaches coded in software for sequentiell processing, represents the state of the art concerning manned combat aircraft in use today.

As far as UTAs or UCAVs are concerned the obtainable level and performance of automation utilizing conventional techniques is not sufficient. Among others it would require too much of externed operstor´s control intervention and hence pose very hard requirements for the data link.

To alleviate this problem, the objective and challenge is to replicate the operator´s brain in the vehicle by artificial brain like information processing structures. For this purpose computational and machine intelligence (CMI) techniques as summarized in Figure 3 and dealt with in a little more detail under paragraph 3 and in [1] can be applied.

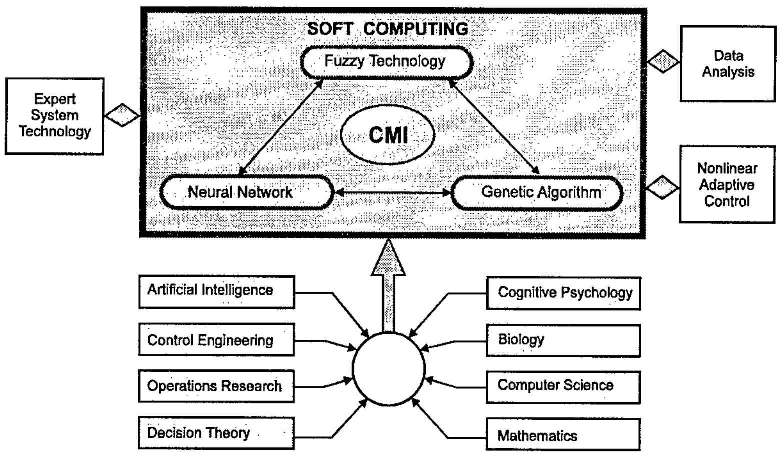


Figure 3: Soft-Computing/CMI and contributions from other areas

Often today they are aggregated under the notion of soft computing.

With that, technologies, techniques and methods are available, by means of which the cognitive abilities of humans for detection, classification, identification, assessment of a situation and of objects in it as well as for goal oriented behavior can attempted to be automated.

This is accomplished by designing and implementing corresponding artificially intelligent control elements, which roughly can be classified in to the different levels as indicated in Fig. 4.

These levels can be assigned to the functional levels of Fig. 2 accordingly. For further details it must be referred to the corresponding literature such as [3].

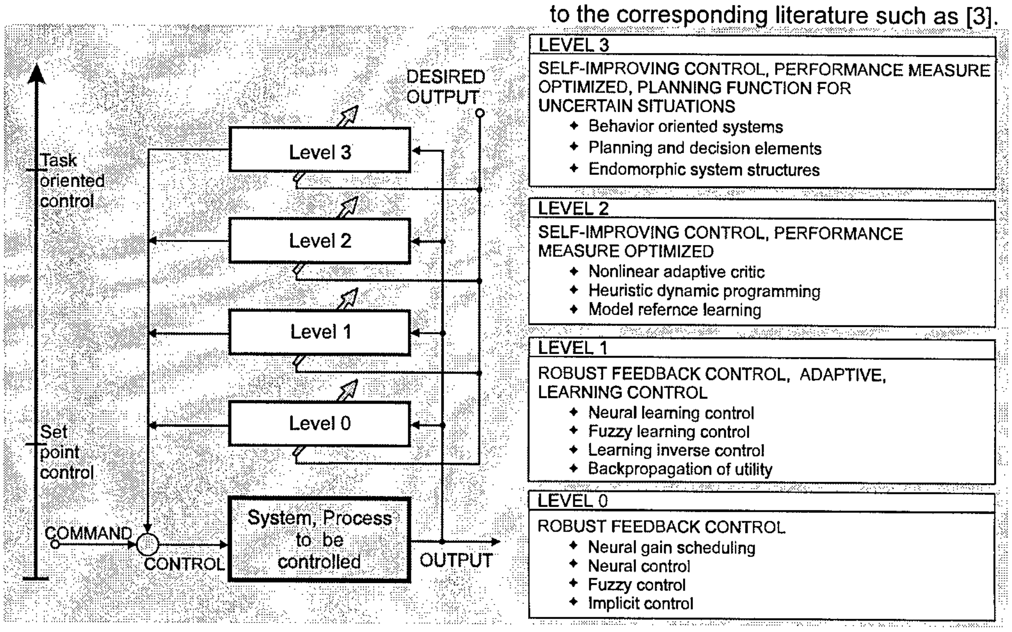


Figure 4: Levels of intelligent, knowledge-based control

Ever increasing complexity of systems is gradually leading to the limits of conventional and even intelligent control. In this context a complex dynamic system is characterized by the terms dimensionality, uncertainty and vagueness, interconnection of many subsystems as well as data and information explosion. To a large extent this applies to future unmanned tactical systems.

To cope with the said limits of control and automation of such systems, the transition to selforganizing autonomy must be performed and ways to design, built and operate autonomous systems must be established. The remainder of this paper is dealing with aspects of this challenge.

3 AUTONOMOUS SYSTEMS

Autonomy is the ability to function as an independent system, unit or element over an extended period of time, performing a variety of actions necessary to achieve predesignated objectives while responding to stimuli produced by integrally contained sensors. The following characteristics are therefore typical of an autonomous, behavior-oriented system:

- An "environment" (real world) is allocated to the system
- There is an interaction between the system and the environment via input and output information and possibly output actions
- The interactions of the system are concentrated on performing tasks within the environment according to a goal-directed behavior, with the system adapting to changes of the environment.

The interaction of the systems with the surrounding world can be decomposed into the following elements of a recognize-act-cycle (or stimulus-response-cycle).

- Recognize the actual state of the world and compare it with the desired state
  (which corresponds to the goal of the interaction). (MONITORING)
- Analyse the deviations of actual and desired state. (DIAGNOSIS)
- Think about actions to modify the state of the world. (PLAN GENERATION)
- Decide the necessary actions to reach the desired state. (PLAN SELECTION)
- Take the necessary actions to change the state of the world. (PLAN EXECUTION)

To perform these functions, first of-all appropriate sensor and effector systems must be provided, as mentioned earlier. In the case of unmanned autonomous systems information processing means must be incorporated that apply machine intelligence to perform the tasks mentioned.

At this point and in this context the following question shall be addressed:

What is computational, machine or more generally artificial intelligence? In relation to the issues and topics treated here, the following answer shall be given.

- Systems/units have no artificial intelligence if a program/software „injects" them with what they have to do and how they have to react to certain pre-specified situations.
- Systems/units have artificial intelligence if their „creator" has given them a structure - not only a program - allowing them to organize themselves, to learn and to adapt themselves to changing situations.

Thus intelligent structures must be able to comprehend, learn and reason.

4 ENABLING NEW INFORMATION TECHNOLOGY

Paradigm shift to brainlike structures

The expected unprecedented advances in computing based on the conventional architecture, where processing is performed sequentially, do not yield the power for computational and machine intelligence.

There is a paradigmatic complementary shift from symbolic artificial intelligence techniques to a new paradigm, which is inspired by modelling the conscious and unconscious, cognitive and reflexive function of the biological brain.

Important related computing methodologies and technologies include inter alia fuzzy logic, neuro-computing and evolutionary and genetic algorithms as summarized in Fig. 5.

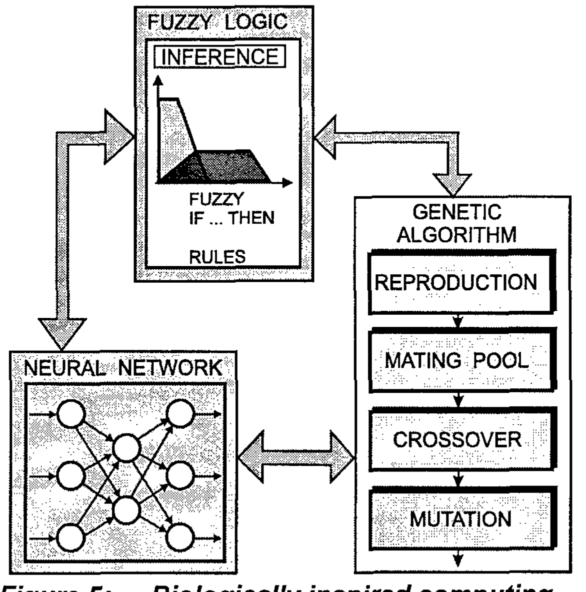


Figure 5: Biologically inspired computing technologies

Fuzzy Logic

The theory of fuzzy logic provides a mathematical framework to capture the uncertainties associated with human cognitive processes, such as thinking and reasoning. Also, it provides a mathematical morphology to emulate certain perceptual and linguistic attributes associated with human cognition. Fuzzy logic provides an inference morphology that enables approximate human reasoning capabilities for knowledge-based systems. Fuzzy logic/fuzzy control has developed an exact mathematical theory for representing and processing fuzzy terms, data and facts which are relevant in our conscious thinking.

A unit based on fuzzy logic represents an associator that maps crisp spatial or spatiotemporal multi-variable inputs to corresponding associated crisp outputs. The knowledge which relates inputs and outputs is expressed as fuzzy if-then rules at the form IF A THEN B, where A and B are linguistic labels of fuzzy sets determined by appropriate membership functions.

Fuzzy rule based systems enable endomorphic real world modelling. With this technology human behavior can be emulated in particular as far as reasoning and decision making and control is concerned taking into account the pervasive imprecision of the real world. Fuzzy logic strongly supports realistic modelling and treatment of reality.

Artificial Neural Networks (ANN)

Neural Networks are derived from the idea of imitating brain cells in silicon and interconnecting them to form networks with self-organization capability and learnability. They are modeled on the structures of the unconscious mind.

Neurocomputing is a fundamentally new kind of information processing. In contrast to programmed computing, in the application of neural networks the solution is learnt by the network by mapping the mathematical functional relations. Neural networks are information processing structures composed of simple processor elements (PE) and networked with each other via unidirectional connections. The "knowledge" is contained in the variable interconnection weights. They are adjusted during a learning or training phase and continue to be adapted during operational use. With this capability the ANN represents an associator (like a fuzzy logic unit) that maps spatial or spatio-temporal multi-variable inputs to corresponding associated outputs. However, in contrast to a fuzzy-rule-based system the mapping function is learnt by the ANN. Neural Networks are capable of acquiring, encoding, representing, storing, processing and recalling knowledge. These are important prerequisites for endomorphic real world modelling.

Genetic and Evolutionary Algorithms

Genetic and evolutionary algorithms represent optimization and machine learning techniques, which initially were inspired by the processes of natural selection and evolutionary genetics.

To apply a genetic algorithm (GA) potential solutions are to be coded as strings on chromosomes. The GA is populated with not just one but a population of solutions, i.e. GA search from a population of points rather than from a single point. By repeated iterations a simulated evolution occurs and the population of solutions improves, until a satisfactory result is obtained. This is accomplished by iteratively applying the genetic operators reproduction, crossover and mutation.

Computer simulation is a viable tool to optimize behavior oriented systems by utilizing genetic or evolutionary techniques. Ever increasing processing speed enables the quick motion representation of events and processes, for which nature requires millions of years.

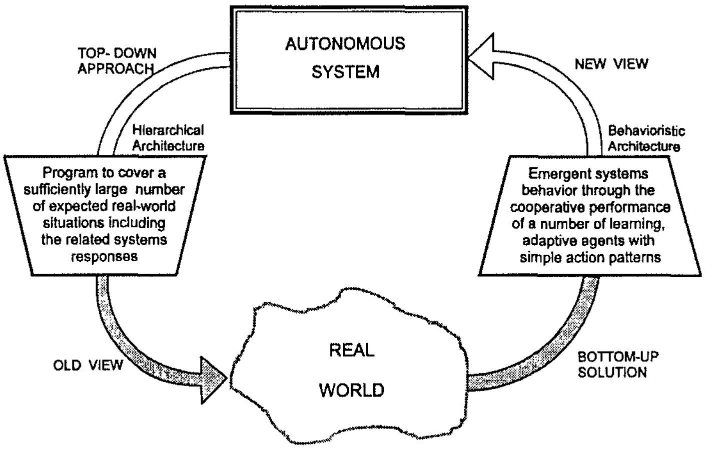


Figure 6: ***Top-down vs. bottom-up approach***

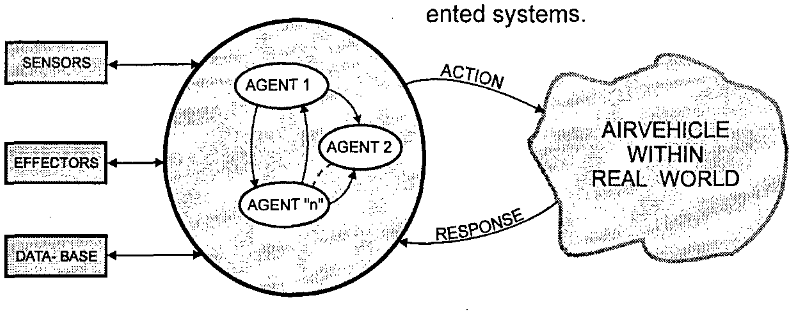
Conclusions

It was shown that fuzzy and artificial neural network techniques enable the endomorphic modelling of real world objects and scenarios. Together with conventional algorithmic processing, classical expert systems, probabilistic reasoning techniques and evolving chaos-theoretic approaches they enable the implementation of recognize-act cycle functions as mentioned. Genetic and evolutionary algorithms can be applied to generate and optimize appropriate structures and/or parameters to acquire, encode, represent, store, process and recall knowledge. This yields self-learning control structures for dynamical scenarios that evolve, learn from experience and improve automatically in uncertain environment. Ideally, they can be mechanized by a synergetic complementary integration of fuzzy, neuro and genetic techniques. These techniques support the move towards adaptive knowledge based systems which rely heavily on experience rather than on the ability of experts to describe the dynamic, uncertain world perfectly. This is accomplished by consideration of the tolerances for imprecision, uncertainty and partial truth to achieve tractable, robust and low cost solutions for complex problems.Thus, these techniques in conjunction with appropriate system architectures provide the basis for creating behavior-oriented autonomous systems.

5 CONCEPTUAL IDEAS

System architectures

The viable architecture must represent the organization of the systems intelligence and capability to behave, to learn, to adapt and to reconfigure in reaction to new situations in order to perform in accordance with its functionalities. Based on fundamentally different philosophies regarding the organisation of intelligence, two different architectures can be basically considered (Fig. 6). With the well known top-down approach as prevalently used to date a hierarchically functional architecture results. It structures the system in a series of levels or layers following the concept of increasing precision with decreasing intelligence when going from top to bottom. Implementation is characterized by the fact that for as many contingencies as possible the allocated system behavior is fixed in top-down programming. In fact, the real world is so complex, imprecise and unpredictable that the direct top-down programming of behavioral functions soon becomes very difficult if almost not impossible.



AGENTS						
SENSOR DATA FUSION	PERCEPTION, SITUATION ASSESSMENT	PLANNING	....	PILOTING	THREAT	COMMUNI-CATION

Figure 7: System representation by agents

Considerably different from the hierarchical structure is the subsumption architecture. It is based upon building functionality and complexity from a number of simple, parallel, elemental behaviors. It is sometimes called the behaviorist architecture and is based on a buttom-up approach. In this approach, so-called agents are implemented with the most simple action and behavior patterns possible so that the resulting emergent system behavior corresponds to the desired global objective. The system is able to adapt itself to changing situations in the environment by learning. The specific local intelligence of the individual agents generates a global intelligent behavior of the integrated overall system. Multi-agent systems are complex and hard to specify in their behavior. Therefore there is the need to endow these systems with the ability to adapt and learn. This can be acomplished by the application of the technologies mentioned before.

A simplified block diagram of an autonomous system based on such a concept of cooperative AI/KB-Agents, is depicted in Fig 7. The objective is to implement as many simple agents as possible with the associated behavior pattern, which then make the system act in a flexible, robust and goal-oriented manner in its environment through their additively complementary interaction. To enable the generation of emergent characteristics it must be ensured that the agents can influence each other mutually. Emergent functionality is one of the major fields of research dedicated to behavior-oriented systems.

Intelligent hardware/software agents will fuse sensor information, monitor critical variables, generate optimized plans, alert operators through communication to problems as they arise and recommend optimized solutions in real time. Response agents capture basic data, communication (forecast and other information) and apply optimization technology to generate new plans based on changed conditions and states.

Design Considerations

Like in Engineering, it is also an indispensable prerequisite for an autonomous system that it is designed, constructed and trained according to a strict methodical approach. Fig. 8 shows such an approach in a very simplified form from today's technological point of view [4].

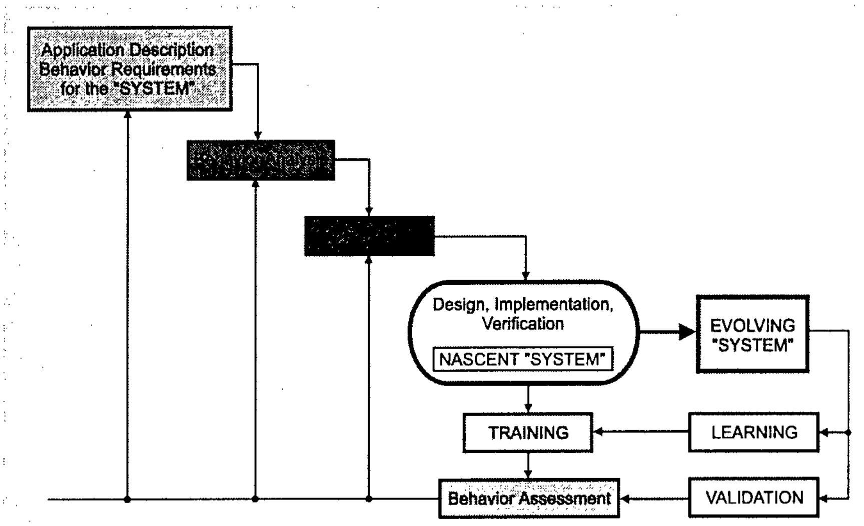


Figure 8: Engineering of the autonomous system

It starts with the description of the physical system, its application, the initial environment, and the behavior requirements, with the latter being usually informally stated in natural language. The following behavior analysis is one of the major tasks. This step involves the decomposition of the target behavior in simple behavioral components and their interaction. Part of the specification is the architecture of the intelligent control system. It is the second key point during the engineering process. With the specification all information is available to design, implement and verify a nascent system, which is endowed with all its hardware and software components, however, prior to any training.

Based on a suitable training strategy the system acquires its knowledge during a training phase which is mandatory and prerequisite for appropriate behavior of the system. Training can usually be speeded up applying simulation including virtual reality. Within this context environments can be used that are much more changeable than the real ones.

After completion of training the behavior is assessed with respect to correctness (target behavior), robustness (target behavior vis-à-vis changing environment) and adaptiveness. Based on this assessment, further iterations during the engineering steps might become necessary in order to make the satisfactorily behaving system evolve from them in a step by step sense.

Implementation issues

Implementation issues like

- hardware for computational and machine intelligence
- software technology, software generation techniques
- autonomous control technology
- autonomous planning and routing
- integrated system structures and functions
- adaptive autonomy management

could not be treated here. It is referred to the Literature, e.g. [5].

6 EMERGENCE OF AUTONOMOUS SYSTEMS

The critical technologies, such as the new paradigm information and control technologies are indeed highly developed activities, however still mainly in universities and industry R.a.D. branches. Thus a time interval of 10 to 20 years is likely to elapse, until applications can be expected within systems as treated here.

Beyond the enabling technologies further technical issues such as

- maturity assessment
- system concepts
- critical experiments
- validation, certification techniques
- future research focus

shall be emphasized, because they critically influence the emergence of autonomous systems. Stepping back to the first chapter and recalling the interdependence of the Requirements Pull and the Technology Push it is of paramount importance for research planners to identify applications and requirements indicating the indispensable need for such systems and their capabilities. In this context the Uninhabited Tactical Aircraft (UTA) concept of variable autonomy currently under investigation, offers an ideal platform to perform critical experiments for the evaluation, validation and possibly certification of techniques and technologies.

Autonomous unmanned systems will be designed such that they offer fully autonomous operation. However, provisions will be incorporated allowing a human to monitor the system's operation and to intervene if required.

7 FINAL REMARKS

Complexity is a central problem in advanced system theory and engineering. The concept of building a high performance system around a central computer with top-down programming has long become obsolete. Well organized complexity with distributed CMI as briefly treated here is the way of the future.

Significant changes are currently taking place in the new information technology (IT) and other technological areas as far as functional capabilities, performance, characteristics and cost are concerned. These changes will support the new way and influence the users of related technologies and the supporting industries as well as their technical and organisational structures. Organizational structures have always reflected system structures. The rate of change and related realizations will exceed normal evolution and will have great social impacts accompanying the technological and functional advances. Instead of spin-offs considerable spin-in effects from commercial research and industry will impact military applications. Simultaneously a global availability of commercial High-Tech must be assumed.

In order to accommodate all this, the strategies of users and industry must be adapted accordingly. Looking at the interdependence of requirements, technologies, procurement processes and time behavior, 10 years is a short period.

WE MUST BEGIN NOW!

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